EXHIBIT C

Optics in Photography

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Perspective

The Center of Perspective

When we use photography to make a permanent record of something we have seen, we are endeavoring to represent a three-dimensional aggregate of objects upon a plane surface. Thus, a photograph is a point projection of a three-dimensional scene, commonly referred to as a "perspective" view, with the "center of perspective" at the camera lens itself.

Optically, our eye is nothing but a camera, and when we look at a scene with one eye open we actually see the same kind of perspective as is recorded by a camera. We could, if we wished, plot out a picture of an assemblage of objects upon a sheet of glass erected between our eye and the objects, as indicated in Fig. 1.1. In this diagram, the eye is supposed to be at *P*, and the appearance of the house as seen by this observer is shown traced on the sheet of glass. The only difference between this glass-plate picture and the picture formed by a pinhole camera is that in the camera

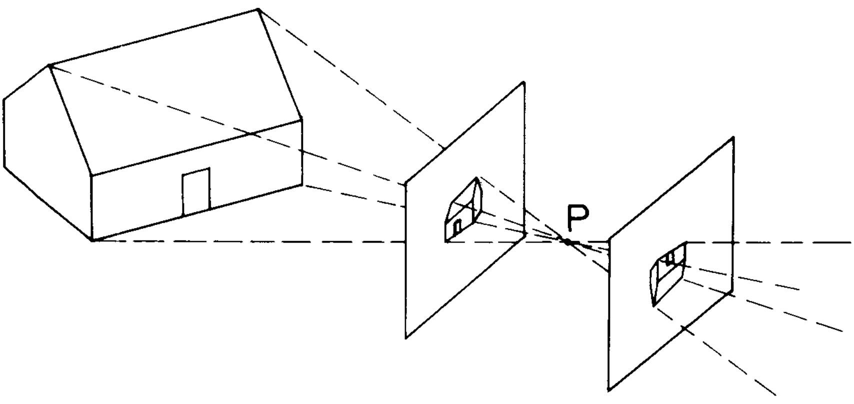

Figure 1.1. The meaning of "center of perspective."

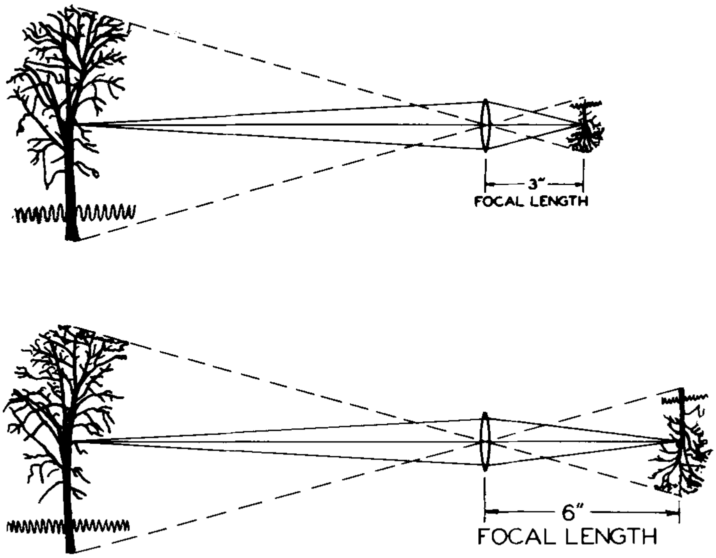

Figure 1.2. A lens of long focus produces a larger image than one of short focus.

the rays cross each other at the pinhole (at *P* in the diagram) and are intercepted by a sensitive film placed behind it. The inverted picture projected on the film will be identical with that traced on the glass plate, provided the film and the glass plate are parallel to each other and are both the same distance from *P*. The point *P* is then the "center of perspective" of the photographed picture. If a lens is used instead of a pinhole, the entrance pupil* of the lens is the center of perspective, and everything that is said here on the subject of perspective applies equally well to the pinhole or to the lens camera. A photograph is thus a two-dimensional rendering of a three-dimensional object, the projection lines all passing through a common center. The size of the projected image will depend on the distance from the center of projection to the film plane, but all images on parallel film planes projected through the same perspective center will be geometrically similar.

We thus reach the important conclusion that we shall obtain the same view of a three-dimensional object or group of objects with any camera whatsoever, provided that the position of the camera lens is fixed and the film plane is in a fixed direction. A lens of long focus will merely produce a larger picture than a lens of shorter focus (Fig. 1.2).

*The entrance pupil is the image of the diaphragm as seen from the front of the lens.

Conventions in Perspective

For many centuries, it has been the established custom to draw or paint a picture as if it were projected upon a vertical plane, and in photography we ordinarily try to follow this rule. If by accident or design we hold the camera during exposure in such a way that the film plane is not vertical, then vertical lines in the object will appear to lean toward each other in the photograph (keystone distortion). The effects of tilting the camera upward or downward are shown in Fig. 1.3 and Fig. 1.4, respectively. This is not a defect of the photographic process, for the camera is indeed recording faithfully what we would see if we looked with one eye in the same direction as the camera was pointing. The difference is that when we see lines apparently converging but known to be parallel, we unconsciously interpret them as being parallel; indeed, we can actually detect the presence of

Figure 1.3. Keystone distortion resulting from an upward tilt of the camera.

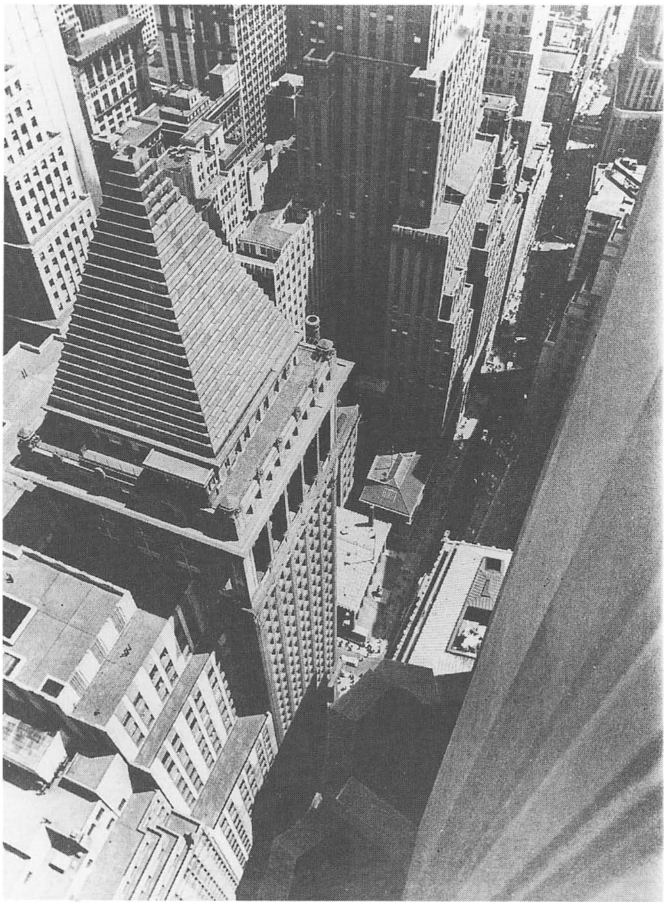

Figure 1.4. Keystone distortion resulting from a downward tilt of the camera.

a small amount of genuine convergence if it exists. However, we do not object to a *sideways* tilt of a camera, causing horizontal parallel lines to converge (Fig. 1.5), probably because this corresponds simply to a change in the horizontal direction of view, our most common visual experience. In printing such a photograph, great care must be taken to keep vertical lines vertical on the print.

It appears that an upward or downward tilt to a camera is undesirable only if it is present to a moderate extent, but very little objection is raised to converging vertical lines if the upward or downward tilt is greater than about 30°. In photographing tall buildings, a strong convergence is a commonly used device to suggest height.

Figure 1.5. The effect of tilting a camera sideways.

If it is necessary to photograph a tall building from the ground without converging verticals, we can either rectify the convergence by use of a tilted enlarger (see page 203) or we can use a camera equipped with a "rising front." This is a device for elevating the lens, and since the image moves with the lens, the top of the tall building will be brought onto the film without the necessity of tilting the camera. In this case we must use a lens that will give good definition over the greatest angle required, namely, θ in Fig. 1.6. Many lenses will not do this unless stopped down very

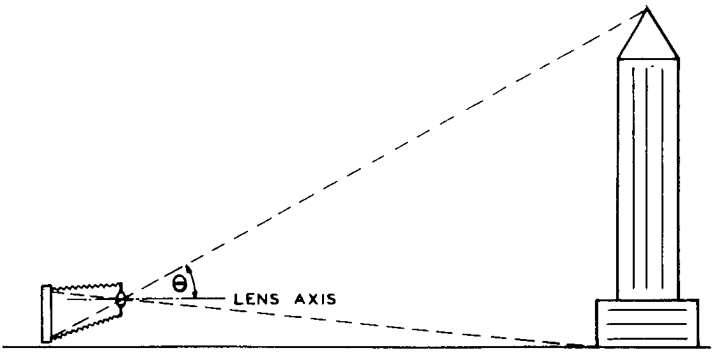

Figure 1.6. Illustrating the use of a rising front in photographing tall buildings.

considerably. To carry the procedure still further, a "swing back" is sometimes used; the essential requirement is, however, to keep the planes of object and film parallel to each other. A typical camera for this purpose is shown in Fig. 1.7.

Another useful rule for satisfactory perspective is that we should not include too wide an angular field of view in one picture. If we stand in a room and let our eyes roam over the walls and ceiling, we realize that we are looking critically at only a small part of the room at any one time. Indeed, the eye can see clearly over a half-angle of perhaps 10° from the center of the field. We can see large objects, and movements of any kind, over an angle of perhaps 25° from the center of the field. To see a wider angle than 25° requires that we roll our eyes consciously and scan the objects one at a time.

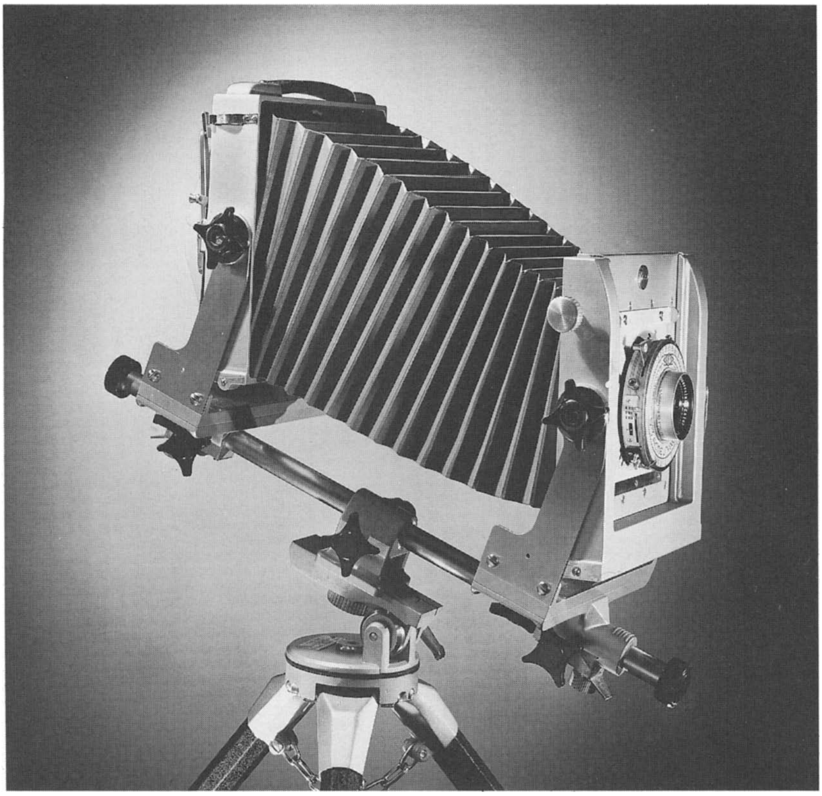

Figure 1.7. The Calumet view camera.

By far the most important rule for correct perspective in photography is that the final print must be viewed from approximately its correct center of perspective, so that the angles subtended at the eye by the various images in the picture will be the same as the subtense angles of the original objects at the camera lens. For contact prints, the center of perspective corresponds to the actual location of the lens in the camera, opposite the middle of the picture and distant from it by the focal length of the camera lens. For enlargements, the distance of the center of perspective from the print is found by multiplying the focal length of the camera lens by the enlargement ratio. Thus, for a negative made in a 35mm camera with a 50 mm (2-inch) lens, and enlarged 10 times in printing, the center of perspective is at 20 inches from the print, and the picture should be viewed from this point. The gain in realism obtained by enlarging small negatives in this way is quite marked and often astonishing.

The lateral position of the eye in relation to the center of perspective is also important. This fact explains the serious distortion that results when we look at a motion-picture screen from the end of the front row of seats, the center of perspective being actually located on a line joining the projector to the screen. In planning a large mural, which is to be viewed from the floor of a room, it is advisable to have the camera low and use the rising front. The opposite effect, with the camera looking down on the subject, would be very unpleasant in such a case.

The Field Covered by a Lens

Every lens projects light onto a circular field that is limited in size by the vignetting or cutting of oblique light by the lens barrel. However, in very few lenses is the definition sharp to the extreme limit of this circle of illumination. Since good definition is required in any practical application of the lens, it is customary to state the field of a lens in terms of the angle over which good definition is obtainable (Fig. 1.8). This angle generally increases somewhat as the lens is stopped down to a smaller aperture.

Since most photographs are taken on a square or rectangular film area, it is necessary that the film format should fit into the circle of good definition of the lens. Thus, the diameter of this circle must be equal to, or greater than, the diagonal of the film.

The "Normal" Focal Length for a Camera Lens

For ordinary photography, the "normal" field is usually such that the diagonal of the negative is equal to the focal length of the taking lens. This

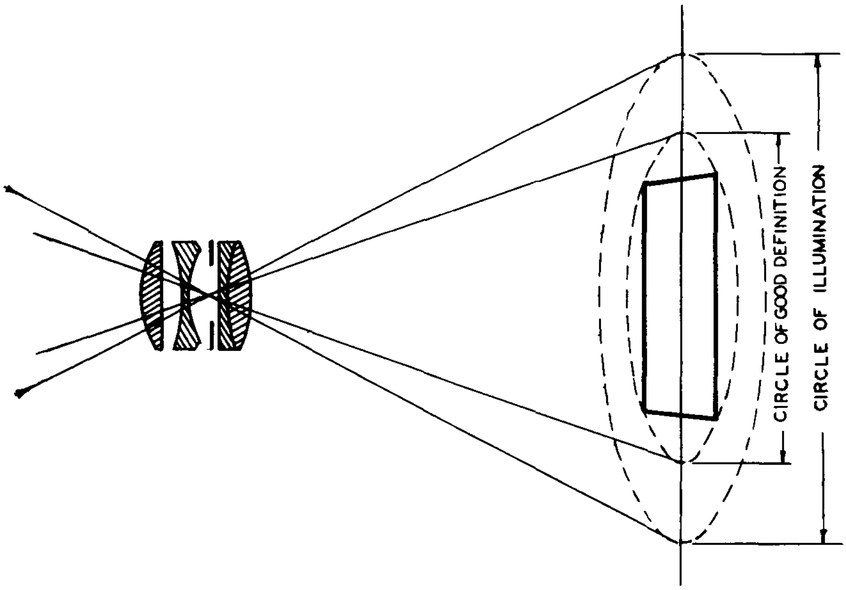

Figure 1.8. The circle of illumination and the circle of definition of a lens.

computes to be a total field of 53°, or a half-field of 26.5°. As has been mentioned, this angle is rather wider than the eye can cover at a glance, but in practice we tend to view most photographs from a point well beyond the center of perspective, and we unconsciously scan a print with our eyes. Such an angle of view is therefore not objectionable. Many photographic prints, too, are cropped in printing so that the whole of the lens field is not recorded.

A *wide-field* lens will cover an angular semifield of about 30° to 35°, and a true *wide-angle* lens will cover a semifield of 45° to 50° (see Fig. 1.9). Hence, a given film format will be covered adequately by a wide-angle lens having a focal length equal to about half the picture diagonal. Naturally, the field covered by the camera will not be increased by using a wide-angle lens of the same focal length as the normal lens; we can gain field only by the use of a shorter-than-normal focal length.

Some *narrow-angle* lenses are loosely called "telephoto" lenses because they have a longer focal length than the normal lens and thus give a picture to a larger scale. However, the name "telephoto" should be restricted to a lens of a particularly compact type of construction (see page 148), in which the distance from the front of the lens to the film plane is

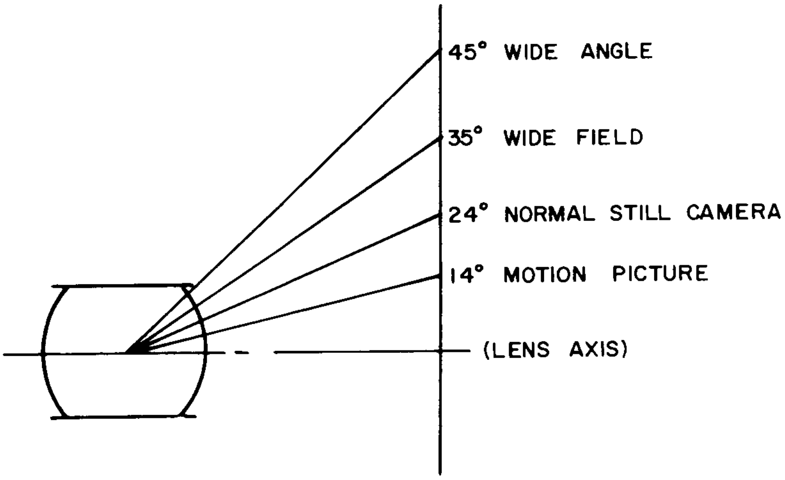

Figure 1.9. Some typical angular fields of lenses.

less than the focal length of the lens.

In motion-picture photography it has always been customary to use relatively long-focus lenses, the "normal" angular semifield being only about 14°. This was probably done originally to keep the camera well away from the actors in order to give them greater freedom of movement along the line of sight. If the camera were close to the subject, with a short-focus lens, the apparent size of the actors would appear to grow or shrink rapidly as they moved, and they might even walk completely out of focus in a couple of steps! Moreover, the "panning distortion" mentioned on page 20 is less noticeable if a long-focus lens is used. The use of a narrow angular field greatly helps the lens designer to make wide-aperture lenses of good quality, which are very necessary with motion-picture cameras having a fixed exposure time.

The matter of perspective must not be overlooked in this connection, as it is generally desirable that the center of perspective should fall at about the middle of the audience in a theatre. Hence the angular field of the camera should be about twice that of the projector, which again brings the camera semifield to about 14°. A wide-angle movie lens then covers a half-angle of about 20°, which is actually less than the field of a normal lens in still photography.

The following table of picture diagonals for some standard film sizes may be of interest. They are taken from ANSI Standard PH3.501-1987.

(a) Still cameras

Film name	Negative area	Diagonal (mm)	Diagonal (inch)
Disc and Minox	8 × 11 mm	13.6	0.53
110	13 × 17 mm	21.4	0.84
half 135	17½ × 24 mm	30.1	1.19
126	28 × 28½ mm	40.0	1.57
135	24 × 36 mm	44.0	1.73
828	28 × 40 mm	48.8	1.92
Sq. 127 (1⅝ × 1⅝ in.)	41 × 41 mm	58.0	2.28
127 (1⅝ × 2¼ in.)	41 × 56 mm	69.4	2.73
Sq. 120 (2¼ × 2¼ in.)	56 × 56 mm	79.2	3.12
120 (2¼ × 3¼ in.)	56 × 82½ mm	99.7	3.93
116	2½ × 4¼ in.	125.2	4.93
¼-plate	3¼ × 4¼ in.	135.9	5.35
	4 × 5 in.	162.6	6.40
	5 × 7 in.	218.5	8.60

(b) Motion-picture cameras

Size	Camera Frame	Camera Diagonal	Projector Gate	Projector Diagonal	Normal focal length of camera lens
	(mm)	(mm)	(mm)	(mm)	
35mm silent	19.05 × 25.37	31.75	17.26 × 23.01	28.76	2 inch (50 mm)
35mm sound	16.03 × 22.05	27.26	15.24 × 20.96	25.91	2 inch (50 mm)
16mm	7.42 × 10.22	12.63	7.21 × 9.65	12.05	1 inch (25 mm)
Super-8	4.22 × 5.77	7.15	4.01 × 5.36	6.69	½ inch (13 mm)
8mm	3.51 × 4.80	5.95	3.28 × 4.37	5.46	½ inch (13 mm)

"True" and "Apparent" Perspective

From the preceding discussion it should be clear that if we look at a photograph from some point other than its true center of perspective, we must expect to see a distorted representation of the original scene. For instance, if our eyes are considerably too far away from the picture, foreground objects will appear too large, and background objects relatively too small. This effect is particularly noticeable in photographs taken with a wide-angle lens, such as that in Fig. 1.10. The center of perspective of the lower photograph is at about 6 inches from the print, and if our eye is placed there, we have the impression that we are looking at a car from a reasonable distance away. For the upper picture, a wide-angle lens was used and the camera was moved very close to the car. The center of perspective of the

tion, and lateral color, when the lens is used at unit magnification. The design problem is thus greatly simplified if a lens is made symmetrical, for each half needs to be corrected only for the longitudinal aberrations, spherical, chromatic, astigmatism, and field curvature. Even when the conjugate distances of object and image from the lens are decidedly unequal, a symmetrical lens is still almost perfectly free from these transverse aberrations. This was one reason for the great popularity of symmetrical anastigmats between about 1890 and 1910. In a "convertible" lens, each half is so well corrected that it can be used alone if desired.

Process and copying lenses are generally of a symmetrical type of construction because neither distortion nor lateral color can be tolerated in such a lens. Distortionless wide-angle lenses for aerial survey work are generally almost symmetrical for the same reason.

The Telephoto Lens

This is a lens of a special type of construction, comprising a positive front component widely separated from a negative rear component. As is indicated in Fig. 2.24(a), this form of construction has the property that the second principal plane lies outside the positive end of the system. The total length from the front lens vertex to the image plane is therefore less than the focal length, a real advantage in lenses of very long focal length. However, it is more difficult to achieve good aberration correction in a telephoto lens than in a lens of a more normal type; consequently, a telephoto lens is used primarily when compactness demands it.

It is common practice with some manufacturers to call any lens a "telephoto" if its focal length is longer than the normal value for that

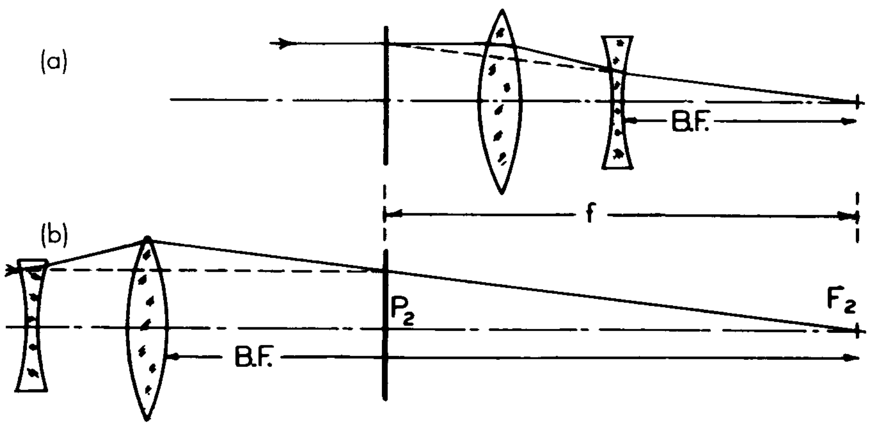

Figure 2.24. (a) The telephoto and (b) the reversed telephoto lens system.

particular type of camera. This practice is, however, misleading and should be avoided. Telephoto lenses are discussed on page 148.

The Reversed Telephoto Lens

If the negative component of a telephoto lens is turned toward the distant object, a system is obtained in which the *back focus*, or distance from the rear lens vertex to the film plane, is exceptionally long, often as long as or longer than the focal length of the lens [Fig. 2.24(b)]. Such a system is useful whenever a long clearance is required between lens and film. The earliest application was in the 3-strip Technicolor camera where a beam-splitting prism was mounted behind the lens to separate the three colored images. Then it became common in short-focus lenses for small movie cameras to provide space for a reflex viewfinder or a turret and the shutter. Today, reversed telephoto lenses are universally employed in wide-angle lenses for single-lens reflex (SLR) cameras, where the tilting mirror and focal-plane shutter require at least 35 mm clearance.

The Simple Magnifier or "Loupe"

When a lens is held close to the eye to act as a magnifier, the object must be placed approximately at the anterior focus of the lens in order that each point in the object will send a beam of parallel light to the eye. The apparent angular size of the image, as seen by the eye, will then be equal to the angle subtended by the object at the front principal point of the lens. The entire advantage of using such a magnifier is, therefore, that it enables us to bring an object exceptionally close to our eyes without having it go out of focus.

Assuming that the least distance of distinct vision for an ordinary unaided eye is 10 inches or 250 mm, the *magnifying power* of a lens of focal length f, when held close to the eye, will thus be equal to the simple ratio

$$\text{Magnifying Power} = \frac{250\text{ mm}}{f} .$$

The Compound Microscope

The compound microscope consists of an *objective* lens that forms a real magnified image of the object, and an *eyepiece* to examine this image. If the objective lens magnifies m_1 times at a certain tube length and the eyepiece has a magnifying power of m_2, then the overall magnifying power of the microscope at that tube length is equal to the product of m_1 and m_2. Since these magnifications are marked on the objective and eyepiece, respec-

$f/1.6$ to $f/1.0$, and generally consist of a pair of cemented doublets spaced apart, with a negative field flattener close to the film plane. For the highest apertures, an additional lens element is often added between the two main components.

For ordinary slide projectors, however, lenses of the Triplet type are generally employed. The focal length of the projector lens is often about twice that of the camera, and the angular fields are small, about ±7° for movie projectors and ±14° for slide projectors.

Telephoto Lenses

It was mentioned on page 49 that the telephoto lens consists of a positive front component widely separated from a negative rear component, the consequence of this arrangement being that the posterior principal plane is out in front and the total length from front vertex to film plane is shorter than the focal length (Fig. 7.11). The *telephoto effect* is the ratio of the total length to the focal length, and in most telephoto lenses its value is about 0.8. Because of the difficulty of designing good lenses of this type, telephoto lenses are used only when the total length must be kept short, as, for instance, in SLR camera lenses of focal length greater than about 150 mm. Occasionally a 135 mm telephoto lens is encountered, but there is little need to shorten the lens in this focal length, particularly as normal lenses have much smaller aberration residuals.

Some typical long-focus telephoto lenses for 35mm cameras are

Focal length	Semiangular field
400 mm	3.1°
300 mm	4.1°
200 mm	6.2°
150 mm	8.2°.

For focal lengths greater than 400 mm, it is customary to resort to catadioptric systems (see page 163). These can be regarded as extremely

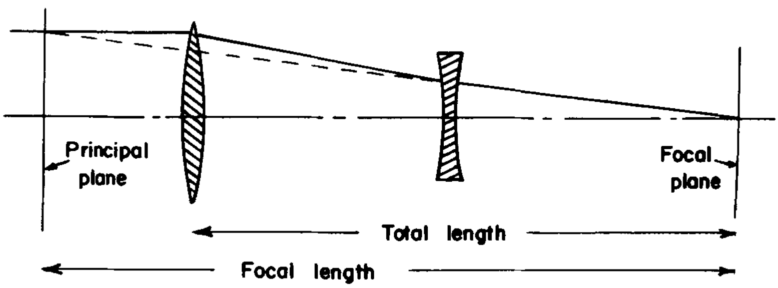

Figure 7.11. Principle of the telephoto lens.

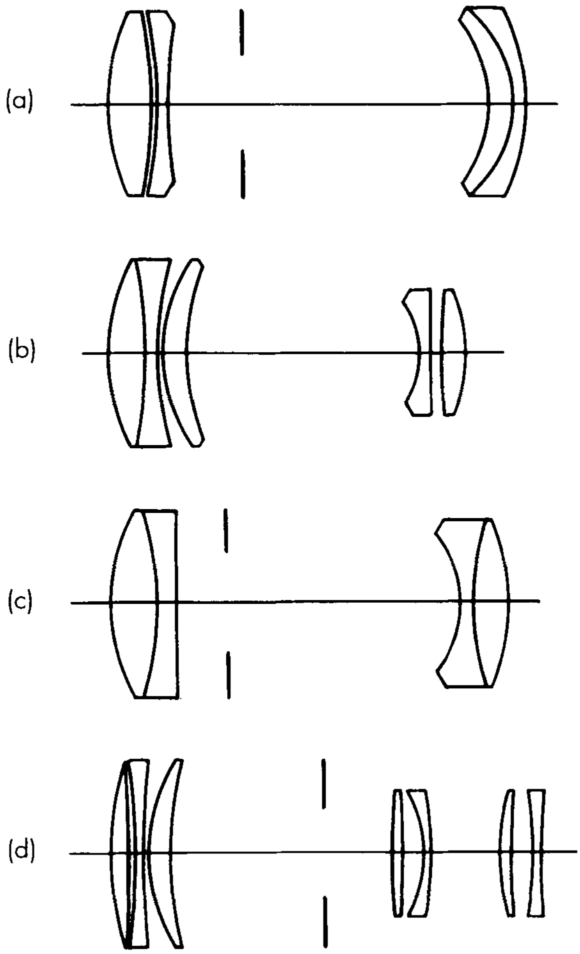

Figure 7.12. Some early telephoto lenses.

short telephotos in which mirrors have been used instead of lenses.

Telephoto lenses were formerly common when the standard film sizes were 4 × 5 and 5 × 7 inches, and they have been used extensively on aerial cameras covering a 9 × 9 inch format (Fig. 7.12). Today, aerial cameras use smaller film sizes, and telephoto lenses are therefore not nearly so important.

When telephoto lenses were first introduced, in the early 1890s, the airspace between the positive and negative components could be varied to change the focal length, making a kind of primitive zoom lens. However, the system had to be focused manually by use of the camera bellows at each

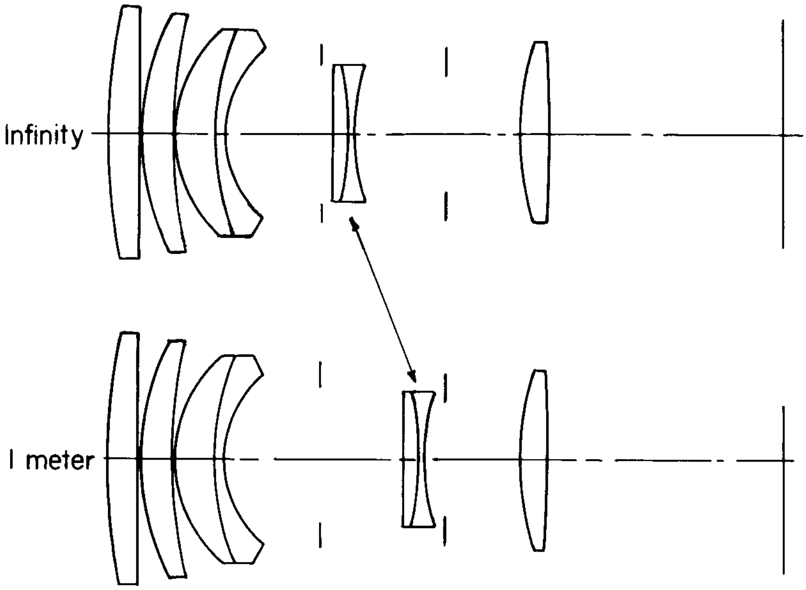

Figure 7.13. The Minolta 135 mm *f*/2.5 telephoto lens, with internal focusing.

focal length, so that they were not really zoom lenses, and the aberration correction fell off badly as the focal length was changed.

During the past few years a number of telephoto lenses have been developed in which focusing on a close object is accomplished by a movement of some internal lens elements, the large heavy front component remaining fixed. The purpose of this is to lighten the load on the tiny motor inside the camera when automatic focusing is provided.

A typical example of this is found in the current Minolta 135 mm *f*/2.8 lens for use on the Maxxum cameras (Fig. 7.13). Here the total length remains at 125 mm, with a telephoto ratio of 0.92, the front four elements and the positive rear element remaining fixed while the internal cemented doublet is moved through 13 mm toward the film when focusing from infinity down to 1 meter.

Reversed Telephoto Lenses

As was mentioned on page 50, the telephoto system can be turned around so that the negative component faces the distant object and the positive component is in the rear. The consequence of this arrangement is that the posterior principal point moves back, and the focal length becomes less